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Radiation Use Efficiency in Dual Winter Cereal–Forage Production Systems

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ABSTRACT

Winter cereal production systems in the northern USA are inefficient with respect to the capture of photosynthetically active radiation (PAR) during the year. Our objectives were to determine radiation use efficiency (RUE) in winter wheat (*Triticum aestivum* L.) and triticale (× *Triticosecale* Wittmack) at low (67–125 plants m^{-2}), medium (116–170 plants m^{-2}), and high (205–332 plants m^{-2}) plant densities and RUE of interseeded red clover (*Trifolium pratense* L.) during two growth periods after cereal harvest. During the linear phase of cereal growth (GS 30–80), RUE averaged across plant density was 3.50 g MJ^{-1} for wheat and 3.21 for triticale in 2004 and 3.37 for wheat in 2006. In 2006, triticale RUE was similar at the low and medium plant density (3.28 g MJ^{-1}) but lower at the high plant density (2.84 g MJ^{-1}). Red clover RUE following wheat and triticale differed by growth period and exhibited varying levels of plant density dependence within growth period. Following wheat at the high plant density, RUE ranged from 1.40 to 1.97 g MJ^{-1} across years and growth periods. Following cereal harvest in mid-July until early October, red clover interseeded in wheat intercepted on average 65% (2004) and 35% (2006) of incident PAR. The wheat–red clover system was more robust than triticale–red clover for grain RUE and intercepting PAR after cereal harvest.

WINTER CEREAL PRODUCTION SYSTEMS in the northern USA are inefficient with respect to the capture of radiation during the year. The majority of winter cereal production fields lay fallow after grain harvest until the following cropping season. Opportunities exist to maximize radiation capture and biomass production. Among practitioners, a common system utilizes frost-seeding techniques to intercrop cereals and legumes. Frost-seeding is commonly performed by mechanically broadcasting seed on a frozen soil and relying on the freezing–thawing process to facilitate seed-to-soil contact for seed germination. Red clover is often selected for frost-seeding because of its tolerance to shading (Taylor and Smith, 1995). Legume biomass functions to control weeds (Liebman and Davis, 2000; Mutch et al., 2003), provide N as a green manure crop (Hesterman et al., 1992; Singer and Cox, 1998), and is a source of forage (Thorsted et al., 2002; Contreras-Govea and Albrecht, 2005).

Management effects on RUE have been evaluated for different wheat cultivars (Yunusa et al., 1993; Calderini et al., 1997), time of planting (Gregory and Eastham, 1996), and N supply (Green, 1987). Reported RUE of winter wheat and triticale to plant density are lacking in the literature. Rosenthal et al. (1993) evaluated RUE of several grain sorghum [*Sorghum bicolor* (L.) Moench] cultivars and plant densities and reported that no significant RUE differences were detected among density and maturity class treatments. Kemanian et al. (2004) also reported no effect of spring barley (*Hordeum vulgare* L.) seeding rate (100 and 250 plants m^{-2}) on RUE. However, Purcell et al. (2002) detected decreasing RUE with increasing soybean [*Glycine max* (L.) Merr.] plant density.

Currently, little information is available on the RUE of dicot forages. Alfalfa (*Medicago sativa* L.) RUE of 1.30 ± 0.14 g MJ^{-1} was reported by Collino et al. (2005) for groups of cuttings growing under a range of nonlimiting temperatures in Argentina (31°24′ S, 61°11′ W). Duru and Langlet (1989) reported RUE of 1.71 ± 0.12 g MJ^{-1} for irrigated alfalfa with no supplemental N growing between May and August and 0.86 to 0.94 g MJ^{-1} for alfalfa growing between August and October near Toulouse, France. Moreover, data are lacking that quantify RUE for two crops during the same growing season, when management of one crop may be detrimental to the other. Our objectives were to determine (i) RUE in winter wheat and triticale at different plant densities and (ii) RUE of interseeded red clover during two growth periods following cereal harvest. Based on the results from a previous study (Blaser et al., 2007), we hypothesized that red clover RUE would be inversely related to cereal plant density during the first growth period following cereal harvest and that red clover RUE during the second growth period would exhibit no residual plant density dependence.

MATERIALS AND METHODS

The field experiment was conducted during the 2004 and 2006 growing seasons at the Iowa State University Agronomy/Agricultural Engineering farm near Ames, IA (42°00′ N, 93°50′ W; elevation 341 m above sea level). 'Kaskaskia' soft red winter wheat and 'Danko Presto' triticale were planted on 15 Oct. 2003 and 7 Oct. 2005 on Canisteo silty clay loam soil (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) using a commercial grain drill with 19-cm row spacing following soybean. Target seeding densities were 100 (low), 200 (medium), and 400 (high) seeds m^{-2}. On 12 Mar. 2004 and 15 Mar. 2006, 'Cherokee' red clover was frost-seeded in wheat and triticale at 16.8 kg seed ha^{-1} (900 seeds m^{-2}) using a drop spreader. On 31 Mar. 2004 and 28 Mar. 2006, 45 kg N ha^{-1} was applied as NH_4NO_3. Plot sizes in 2004 were 209 m^2 for the winter cereals and 35 m^2 for red clover within each cereal plot. In 2006, plot size for both was 209 m^2.

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Abbreviations: LAI, leaf area index; PAR, photosynthetically active radiation; RUE, radiation use efficiency; VPD, vapor pressure deficit.

Cereal establishment density was measured in early spring of 2004 by counting 12, 0.57 m^2 areas in each plot and in the fall of 2005 by counting six 0.57 m^2 areas in each plot. Cereal phenology was recorded every 2 wk from green-up until harvest using the Zadoks's decimal scale (Zadoks et al., 1974) by recording the stage of 12 random plants in each plot. Cereal shoot biomass samples were collected every 7 to 14 d from one 0.38 m^2 quadrat by clipping all biomass to the soil surface. Biomass samples were collected from nontrafficked interior rows in each plot and marked to avoid sampling regrowth during subsequent biomass sampling. Only cereal biomass was included in the biomass sample. Biomass samples were dried in a forced-air oven at 70°C to constant weight. Spikes per m^2 were determined by counting 12, 1-m row lengths before grain harvest. In all cases, nondestructive plant data were obtained from plants in the nontrafficked interior rows. Leaf area index was measured with an LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln, NE). Wheat and triticale were harvested on 15 and 17 July 2004 and both were harvested on 17 July 2006. The straw was baled and removed the day after or the same day as grain harvest.

On 23 July 2004 and 28 July 2006, red clover density was determined by counting two 0.25 m^2 quadrats in each plot. Red clover shoot biomass sampling occurred at least six times in different locations in the same plot during each of two 40-d growth periods with final harvests occurring on 23 Aug. and 5 Oct. 2004 and 25 Aug. and 4 Oct. 2006. All biomass samples were dried in a forced-air oven at 70°C to constant weight. Following the last red clover sampling during each growth period, the entire plot was machine harvested leaving a 6-cm stubble height.

Two line quantum sensors (LI-191SA, LI-COR) were deployed at green-up (3 Apr. 2004 and 6 Apr. 2006) of the cereals on the soil surface in nontrafficked interior rows. Sensors were positioned diagonally from northwest to southeast across three rows during cereal production and across three rows during the red clover phase using stubble from the cereal crop for alignment. After cereal harvest, during the first red clover growth period, one sensor was deployed to measure red clover and cereal stubble PAR transmission, while the other only measured cereal stubble PAR transmission. All red clover was removed from the area around the stubble only sensor. Transmitted PAR from the cereal stubble only sensor was subtracted from the transmitted PAR from the stubble with clover sensor. The amount of PAR intercepted by the stubble in 2004 in the clover canopy was assumed to decrease linearly until 70% canopy closure when the stubble was assumed to be completely shaded by the clover. In 2006, red clover canopy height did not exceed the cereal stubble height during the first growth period. During the second growth period, both sensors measured red clover radiation transmission. Radiation interception was calculated as the difference between incident and transmitted PAR. Incident PAR radiation was measured using a quantum sensor (LI-190SA, LI-COR) mounted on a tripod at a 2-m height at the edge of the field.

All radiation sensors were carefully leveled, cleaned regularly, and had been calibrated by the manufacturer before the beginning of each growing season. All line quantum sensors were removed 1 to 3 d before cereal harvest, within 1 d of red clover harvests, and were deployed within 2 d after harvest. All sensors were connected to a datalogger (21X or CR23X, Campbell Scientific, Logan, UT) and the signal recorded every 60 s and averaged every 60 min in 2004 and 30 min in 2006. Output from the radiation sensors was integrated to obtain daily total incident and transmitted PAR, and these values were used to calculate intercepted PAR. Photon flux density (μmol m^{-2} s^{-1}) from the radiation sensors was converted to energy flux (W m^{-2}) using the conversion of 2.35×10^5 J mol^{-1} PAR (Campbell and Norman, 1998). Radiation transmission data were lost during the first red clover growth period in 2006 because of equipment failure. Monthly air temperature and precipitation for March through September were measured at a weather station 1.5 km from the field site (Table 1).

The reliability ratio for the PAR data was greater than 0.98 so measurement error methods were not needed. The reliability ratio is a measure of the attenuation of the slope in a linear regression if the measurement error is ignored. Multiple diagnostics suggested weighted regression was needed so iteratively reweighted nonlinear least squares was used with inverse variance weight models, although generally the weight was $s^2 = \hat{y}$. A line with a slope and intercept or slope only was developed for each year–crop–growth cycle. The NLIN procedure in SAS v. 9.1 (SAS Institute, 2002) was used to perform each analysis. The slope is the RUE estimator. Cereal biomass data and cumulative intercepted PAR were limited to the linear growth period between GS 30 and GS 80 (Zadoks et al., 1974) to estimate RUE. This period was between DOY 93 and 167 in 2004 and DOY 96 and 173 in 2006. Differences between RUE estimators for each pair of planting density levels within each year–crop–growth period set were examined with both 90% confidence intervals about each RUE estimator and with a hypothesis test on the difference. For each period between crop and year, means pooled across plant densities were examined with contrasts from weighted ANOVA. Results from hypothesis tests were considered significant if $P < 0.05$.

RESULTS AND DISCUSSION

Cereal Radiation Use Efficiency

Plant density did not affect wheat RUE (Table 2) in 2004 or 2006, which averaged 3.50 and 3.37 g MJ^{-1}, respectively. Triticale RUE was not affected by plant density in 2004 and averaged 3.12 g MJ^{-1}. In 2006, triticale RUE at the low and medium plant density (3.29 g MJ^{-1}) was greater than RUE at the high plant density ($P < 0.008$). In 2004, maximum triticale biomass increased 229 g m^{-2} from the low to the high plant density (Table 3). In 2006, maximum triticale biomass decreased 181 g m^{-2} from the low to high plant density. Lower biomass production in wheat and triticale in 2004 was probably related to the excessive May rainfall, which was 96 mm above average, and the cooler than average air temperatures.

In 2004 and 2006, incident PAR was 639 and 688 MJ m^{-2} during the growth period used to calculate RUE (GS 30–GS 80). Wheat intercepted 58 to 70% and

Table 1. Mean monthly air temperature and precipitation near Ames, IA.† Long-term mean is from 1977 to 2006.

Month	Air temperature 2004	Air temperature 2006	Air temperature Mean	Precipitation 2004	Precipitation 2006	Precipitation Mean
	°C			mm		
Mar.	5.6	3.3	2.8	96	74	51
Apr.	11.7	13.3	10.5	61	109	89
May	16.7	16.7	16.4	208	55	112
June	20.0	22.2	21.4	91	21	118
July	22.2	24.4	23.4	50	141	119
Aug.	19.4	22.2	22.0	132	157	122
Sept.	20.0	16.1	18.2	34	191	84

† NWS COOP site Ames 8WSW.

Table 2. Radiation use efficiency (RUE, g MJ^{-1}) of winter wheat and triticale at different plant densities and interseeded red clover during the 2004 and 2006 growing seasons near Ames, IA. Red clover was interseeded at 16.8 kg seed ha^{-1} (900 seeds m^{-2}). Red clover RUE was determined during two 40-d growth periods after cereal harvest each year.

	Cereal					Red clover growth period 1				Red clover growth period 2		
Plant	Plant density	Spike density	RUE	SE	90% confidence interval	Plant density	RUE	SE	90% confidence interval	RUE	SE	90% confidence interval
	plants m^{-2}	no. m^{-2}				plants m^{-2}						
						2004						
Wheat	93†	450	3.78	0.36	(1.51, 5.98)	92‡	1.66	0.23	(1.17, 2.15)	1.97	0.27	(1.34, 2.60)
	170	531	3.28	0.40	(2.27, 4.59)	90	1.79	0.08	(1.59, 1.99)	2.52	0.07	(2.39, 2.66)
	332	685	3.43	0.13	(3.06, 3.80)	70	1.62	0.17	(1.22, 2.02)	1.93	0.14	(1.63, 2.22)
Triticale	125	476	3.11	0.22	(2.48, 3.74)	50	1.41	0.06	(1.26, 1.56)	2.02	0.25	(1.42, 2.62)
	153	516	2.82	0.21	(2.33, 3.31)	88	1.24	0.32	(0.30, 2.18)	1.82	0.11	(1.57, 2.06)
	286	601	3.43	0.32	(2.49, 4.37)	94	0.72	0.21	(0.09, 1.35)	1.70	0.15	(1.38, 2.02)
						2006						
Wheat	67	461	3.40	0.11	(3.19, 3.61)	38				1.45	0.08	(1.28, 1.62)
	122	574	3.37	0.10	(3.19, 3.55)	56	1.50	0.21	(1.10, 1.90)	1.14	0.09	(0.95, 1.33)
	217	579	3.35	0.12	(3.12, 3.58)	70				1.40	0.11	(1.19, 1.61)
Triticale	75	497	3.40	0.14	(3.14, 3.66)	60				1.60	0.13	(1.34, 1.86)
	116	450	3.17	0.08	(3.02, 3.32)	32				2.64	0.32	(1.95, 3.33)
	205	479	2.84	0.09	(2.68, 3.00)	32				3.64	0.41	(2.77, 4.51)

† Cereal plant density was measured in the spring of 2004 and the fall of 2005.
‡ Red clover plant density was measured about 10 d following cereal harvest.

triticale intercepted 63 to 76% of this radiation in 2004 and 79 to 84% and 83 to 91% in 2006 (Fig. 1). Despite intercepting more PAR both years than any other treatment, the high triticale plant density in 2006 was less efficient utilizing the radiation for biomass production. Maximum LAI in 2004 was achieved between DOY 142 and 156 and was 5.1, 4.6, and 4.3 in triticale and 3.5, 3.6, and 3.4 in wheat from high to low plant density, respectively. In 2006, LAI on DOY 168 was 3.5, 3.9, and 3.7 in wheat and 4.9, 4.2, and 4.1 in triticale from high to low plant density.

Wheat and triticale RUE were similar between years (3.41 and 3.06 g MJ^{-1}), averaged across plant densities (Table 4). Averaged across cereal species and plant density, no year effect was observed for RUE (3.25 g MJ^{-1}). However, averaged across year and plant density, wheat had higher RUE than triticale. Estimates of RUE for triticale were not found in the literature. However, these estimates for winter wheat RUE exceeded the values reported by Whaley et al. (2000), who found that winter wheat RUE ranged between 2.2 and 3.3 g MJ^{-1} absorbed PAR for plant densities ranging between 19 and 338 plants m^{-2}. Additionally, Whaley et al. (2000) reported that RUE was greater at lower plant density because of better radiation distribution within the canopy and increased canopy N ratio. Only triticale RUE in 2006 exhibited density dependence in our study, with lower RUE at the highest plant density.

Several possibilities in addition to agronomic practices exist for reported differences in RUE. We report RUE based on intercepted not absorbed PAR using

Table 3. Maximum cereal dry shoot biomass at different plant densities and interseeded red clover (RC) dry shoot biomass during two 40-d growth periods after cereal harvest in 2004 and 2006 near Ames, IA.

	2004			2006		
Plant density	Cereal	RC1	RC2	Cereal	RC1	RC2
	g m^{-2}					
Wheat						
Low	1109.5	652.0	474.4	1636.6	87.8	205.0
Medium	1253.7	518.0	614.4	1456.3	61.6	184.4
High	1344.7	389.2	539.6	1668.4	44.4	226.6
Triticale						
Low	1167.9	273.6	467.6	1889.7	38.4	195.4
Medium	1191.8	228.4	490.0	1838.4	14.4	140.2
High	1396.6	94.8	358.0	1709.2	7.2	131.4

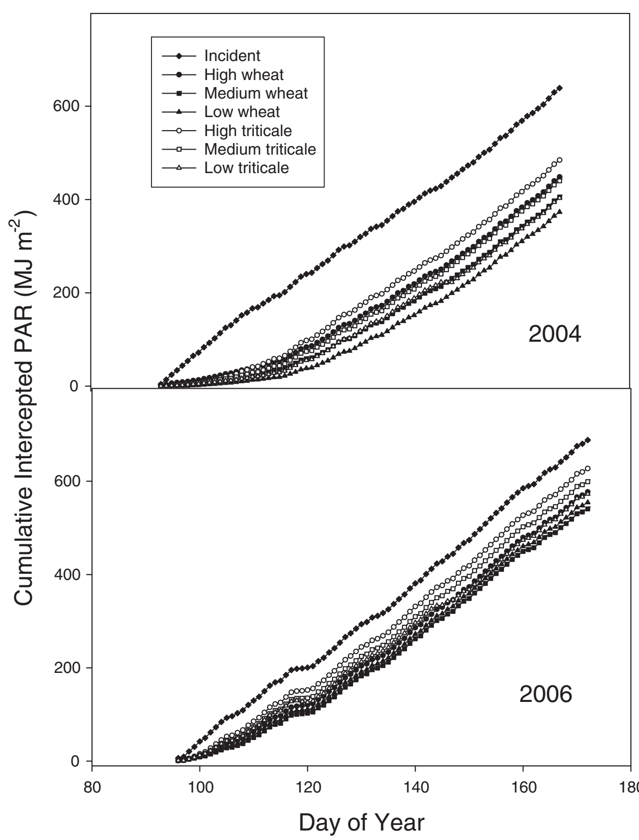

Fig. 1. Cumulative intercepted photosynthetically active radiation (PAR) for wheat and triticale plant densities between GS 30 and GS 80 growth stages (Zadoks et al., 1974) during the 2004 and 2006 growing seasons near Ames, IA.

Table 4. Least squares means from single degree of freedom hypothesis tests of radiation use efficiency (RUE) in wheat (W) and triticale (T) during 2004 and 2006 near Ames, IA, and RUE of interseeded red clover (RC) following grain harvest during two 40-d harvest periods. Mean red clover RUE during the first growth period following triticale is only included for 2004.

Hypothesis test	Pr > *F*	Least squares mean
Wheat 2004 vs. wheat 2006	0.685	3.41
Triticale 2004 vs. triticale 2006	0.879	3.06
2004 vs. 2006	0.877	3.25
Wheat vs. triticale	0.040	3.41 vs. 3.06
RC1-W 2004 vs. RC1-W 2006	0.526	1.62
RC1 2004 vs. RC1 2006	0.895	1.53
RC1-W vs. RC1-T	0.250	1.53
RC2-W 2004 vs. RC2-W 2006	<0.001	2.40 vs. 1.33
RC2-T 2004 vs. RC2-T 2006	0.794	1.85

continuous measurements. Whaley et al. (2000) used point measurements of absorbed PAR and extrapolated linearly between measurement periods. Sinclair and Muchow (1999) reported that interpolation between spot measurements contributes error inversely proportional to the frequency of measurement. Kemanian et al. (2004) demonstrated the importance of adjusting RUE for daytime vapor pressure deficit (VPD). They adjusted RUE for VPD values greater than 1.0 kPa in semiarid eastern Washington. In 2004 and 2006, 87 and 75% of the daytime VPD values were less than 1.0 kPa from April 1 to September 30 from a weather station located about 8 km from the field site. Consequently, we did not adjust our RUE estimates for VPD. These RUE values for wheat and triticale were robust across year and plant density and could be used for estimating RUE in similar environments.

Red Clover Radiation Use Efficiency

Red clover RUE during the first growth period following wheat in 2004 exhibited no effect of wheat plant density ($P > 0.200$). Red clover RUE following triticale during the first growth period was greater following the low compared with the high plant density ($P = 0.014$). Maximum clover biomass differed by 263 g m^{-2} between the low and high plant density treatments following wheat and by 179 g m^{-2} following triticale (Table 3). Interception of PAR differed by only 11 MJ m^{-2} between the low and high plant density treatments following wheat (282–293 MJ m^{-2}) and by 94 MJ m^{-2} following triticale (242–148 MJ m^{-2}). Averaged across cereal and red clover seeding rate, Blaser et al. (2007) reported that red clover biomass was 30% greater at the end of the first 40-d growth period in the low compared with the high cereal seeding rate in 2004. In 2003, this difference was 22% but was not statistically significant. The cereal plant densities in their study at the low and high seeding rate were 95 and 214 plants m^{-2} in 2003 and 103 and 295 plants m^{-2} in 2004, averaged across cereal and red clover seeding rate (Blaser et al., 2006).

Red clover plant density following wheat was 92, 90, and 70 plants m^{-2} at the low, medium, and high cereal plant density and 50, 88, and 94 plants m^{-2} following triticale (Table 2). Blaser et al. (2007) reported no effect of cereal seeding rate on red clover plant densities after cereal harvest in 1 yr and slightly higher (108 vs. 98 plants m^{-2}) red clover plant densities between target cereal seeding rates of 100 compared with 300 seeds m^{-2} in another year, averaged across cereal and red clover seeding rate. An inverse relationship between cereal biomass and red clover biomass was observed in 2004 during the first red clover growth period, but this only affected red clover RUE following triticale at the low and high plant densities. The higher RUE following triticale at the low plant density occurred with 44 fewer red clover plants m^{-2}. This highlights the inhibitory effect of increasing triticale plant density to a red clover intercrop during the first growth period after grain harvest and the compensatory ability of individual red clover plants.

In 2006, red clover RUE during the first growth period was limited to the medium plant density following wheat because of equipment failure. No difference was detected for red clover RUE during the first growth period across year, cereal species, and plant density (Table 4). Although relative differences in RUE were not large across years, red clover biomass during the first growth period in 2006 were 7 to 23% of the 2004 biomass following wheat and 3 to 40% following triticale (Table 3). In 2006, red clover biomass was greatest following the low plant density across cereal and decreased by 49 and 81% in wheat and triticale from the low to the high plant density. In 2006, red clover only intercepted 44 MJ m^{-2} PAR during the first growth period following wheat at the medium plant density compared with 288 MJ m^{-2} in 2004. Red clover plant density was similar in 2004 and 2006 following wheat at the high plant density, yet biomass was reduced by 93%. Wheat biomass was 20% higher in 2006 than 2004 in the high plant density treatment. Although rainfall was only 18% of the long-term average in June 2006, July rainfall was above average. The extreme shading of the intercrop under a dense cereal canopy may delay the physiological transformation that must occur for growth and development of the intercrop once the grain crop is harvested and may partially explain the marked difference in red clover biomass between years.

Red clover RUE during the second growth period exhibited no clear response to previous cereal plant density following wheat. The low and high plant densities had lower RUE than the medium in 2004 ($P = 0.040$ and 0.002), and the medium plant density had lower RUE than the low and high in 2006 ($P = 0.017$ and 0.045). Red clover RUE following triticale during the second growth period exhibited plant density dependence in 2006 but not 2004 ($P = 0.157$–0.274). In 2006, increasing plant density increased RUE by increments of one or more. Intercepted PAR in 2004 ranged from 244 MJ m^{-2} at the low to 201 MJ m^{-2} at the high plant density following wheat and 227 to 199 MJ m^{-2} following triticale. In 2006, intercepted PAR ranged from 156 to 184 and 123 to 49 MJ m^{-2} following wheat and triticale from the low to high plant densities. Biomass was 64 g m^{-2} lower at the high plant density compared with the low following triticale, but RUE was almost 2.3 times higher. Averaged across plant density, red clover RUE following triticale during the second growth period was similar in

2004 and 2006 ($P = 0.794$, Table 4), but not following wheat ($P < 0.001$).

Unlike the consistent RUE response across year within cereal, red clover RUE appears more variable across year and within a specific growth period in a year. Duru and Langlet (1989) reported higher RUE for alfalfa growing from June through August than for alfalfa growing during September. They concluded that factors controlling regrowth stem number and length were critical for reaching maximum radiation interception. In the current work, red clover RUE was more consistent following wheat at the high seeding rate, which falls within the current recommendation for planting winter wheat in the region (300–400 pure live seeds m^{-2}). The range in RUE for this treatment was 1.40 to 1.93 g MJ^{-1} across year and growth period. Although only one red clover cultivar was used in this study, it ranks high among elite cultivars tested in the same location (Singer et al., 2006) and represents the upper limit for biomass production.

CONCLUSIONS

Plant density dependence was detected for RUE in winter triticale but not wheat. Radiation use efficiency was similar across year and plant density within species and winter wheat RUE was higher than triticale. Red clover RUE following wheat within a year was not affected by the residual effect of wheat plant density during the first growth period after cereal harvest and exhibited no clear trend during the second growth period. Red clover RUE following triticale exhibited more cereal plant density dependence but less variability across year. Red clover RUE in dual cropping systems is variable because plant growth rate interacts with previous cereal species and environmental conditions during specific growth periods. Consequently, modeling red clover RUE specifically and perennial forages generally must include adequate variability to account for the complex response.

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